

APL - North Pacific Acoustic Laboratory

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Grant Number: N00014-03-1-0181

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LONG-TERM GOALS

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, and the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) program at the Applied Physics Laboratory (APL-UW) and the Scripps Institution of Oceanography (SIO) is directed toward a complete understanding of the basic physics of low-frequency, long-range, broadband acoustic propagation, the effects of environmental variability on signal stability and coherence, and the fundamental limits to signal processing at long-range imposed by ocean processes. The long-term goal of NPAL is to optimize advanced signal processing techniques, including matched field processing and other adaptive array processing methods, based upon knowledge about the multi-dimensional character of the sound and noise fields and their impact on long-range ocean acoustic transmissions.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 2005		2. REPORT TYPE		3. DATES COVERED 00-00-2005 to 00-00-2005	
4. TITLE AND SUBTITLE APL - North Pacific Acoustic Laboratory				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Washington, Applied Physics Laboratory, 1013 NE 40th Street, Seattle, WA, 98105				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES code 1 only					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 12	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

OBJECTIVES

The scientific objectives of the North Pacific Acoustic Laboratory are:

1. To study 3-D coherence (horizontal, vertical, and temporal) of long-range, low-frequency resolved rays and modes.
2. To explore the range and frequency dependence of the fluctuation statistics of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments.
3. To understand the surprisingly large amount of acoustic energy scattered into the geometric shadow zone beneath deep caustics as measured with the NPAL network of bottom-mounted SOSUS receivers (shadow-zone arrivals).
4. To define the characteristics and determine the causes of ambient noise on ocean basin scales.
5. To elucidate the relative roles of internal waves, ocean spice, and internal tides in causing acoustic fluctuations.
6. To improve basin-scale ocean sound-speed predictions via assimilation of acoustic travel-time and other data into numerical ocean-dynamic models.

APPROACH

NPAL employs a combination of experimental measurements, data analysis, and simulations to address the objectives outlined above. The NPAL network, operated and maintained by the Applied Physics Laboratory, provides an actual laboratory for real-time propagation measurements at a selection of basin-scale distances, the capability to test various transmission signals, and ambient noise measurements at various locations in the Pacific Ocean. The network consists of an acoustic source near the Island of Kauai, HI controlled from Seattle, WA, the legacy SOSUS hydrophone receiver network in the Pacific Ocean, and a data processing and archive center at the Applied Physics Laboratory. Figure 1 illustrates the NPAL network.

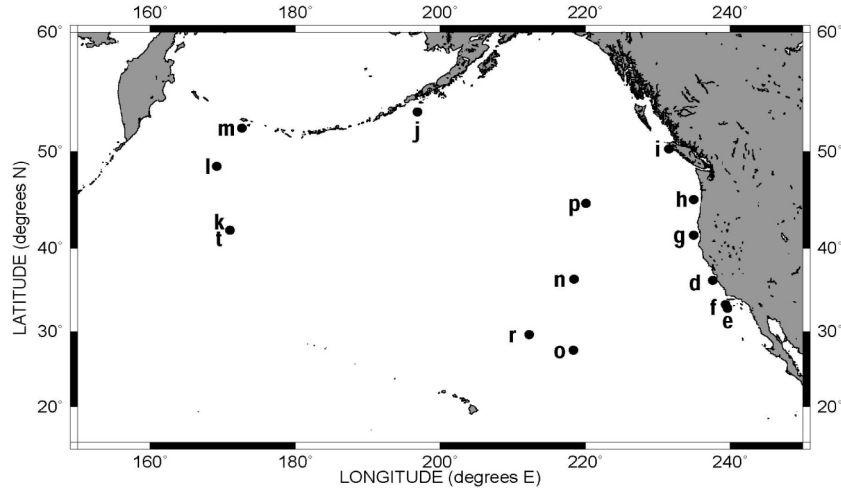


Figure 1. The NPAL network. A transducer near the Island of Kauai (near bottom of Figure) transmits periodically to receivers indicated by black dots and letters. The receivers also collect ambient noise spectral data. The entire network is controlled and monitored from APL-UW.

The most recent NPAL experimental effort consisted of three coordinated experiments. APL-UW conducted the Long-range Ocean Acoustic Propagation EXperiment (LOAPEX), SIO was responsible for the SPICE04 experiment, and MIT and OASIS performed the Basin Acoustic Seamount EXperiment (BASSEX). The Work Completed section of this report discusses the conduct of LOAPEX and its interaction with SPICE04 and BASSEX.

The approach of NPAL also includes collaboration with a number of researchers from several other institutions who provide further analysis of NPAL experimental data and theoretical development. The collaboration is enhanced by holding yearly NPAL conferences usually near Seattle or San Diego.

WORK COMPLETED

The LOAPEX cruise. The 30-day cruise for the Long-range Ocean Acoustic Propagation EXperiment was completed on 10 October near the beginning of this report period. By all measures the experiment is considered a success. LOAPEX directly addressed most of the stated objectives of the NPAL program by providing mid-water low-frequency acoustic transmissions to a number of receivers at a wide variety of ranges. Figure 2 describes the geometry of LOAPEX and the related assets. In particular, those assets include the APL-UW NPAL network of receivers and two vertical line hydrophone arrays installed by SIO. LOAPEX also provided low-frequency acoustic transmissions to the towed horizontal line hydrophone array that was deployed as part of BASSEX.

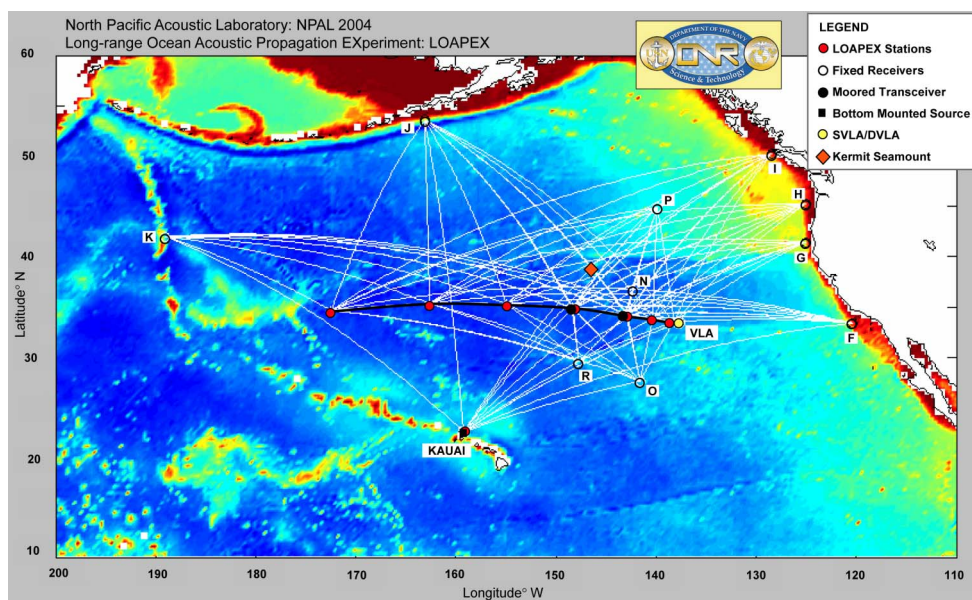


Figure 2. The LOAPEX geometry and assets. Seven red dots along the black cruise path indicate locations from which a low-frequency acoustic source was suspended at various depths from the R/V MELLVILLE. An eighth position was taken near the Kauai acoustic source. The open circles labeled with alphabetical letters represent permanent hydrophone arrays of the NPAL network. The red diamond represents the area of seamounts that were studied during BASSEX. The yellow dot shows the location of two vertical line arrays. The white lines indicate the geodetic paths between source locations and receivers.

LOAPEX obtained a bevy of environmental measurements (including the use of an underway CTD and the deployment of two autonomous Seagliders) and a suite of measurements designed to provide the absolute position and velocity of the acoustic source during transmissions. The transmissions consisted mostly of 20 and 80-minute M-sequences, but CW and ‘prescription’ FM slides were also used. All in all, not counting short engineering transmissions to ensure the proper source level, 5,760 minutes of acoustic transmissions were completed. A full description of the details of the LOAPEX cruise is contained in Mercer et al. (2005).

Following the LOAPEX cruise, a significant effort was put forth to determine the four-dimensional location and velocity of the acoustic source during transmissions. This is important so that incoherence measured at the various receivers, due to source motion, is not falsely attributed to ocean variability. Although source motion was typically only 5 meters during a lengthy transmission, this is still a significant portion of the 20-meter wavelength. By utilizing several independent measurements and a finite element cable suspension model, we have determined the source locations to approximately 1 meter during transmissions making the effect negligible. These data are available to all NPAL researchers on the APL-UW NPAL website <http://pc-lrpgroup.apl.washington.edu>. In addition, work has begun to develop a Doppler “toolkit” for NPAL researchers. The product will use the source position and velocity data to construct time-varying Doppler corrections to receivers at arbitrary bearings and ranges.

The NPAL network. The NPAL network was used extensively during the past year. Transmissions from the Kauai acoustic source continued on the normal schedule of once every four hours on every fourth calendar day, except for a period of 60 days surrounding the LOAPEX cruise when the source transmitted six times every day. The scheduling of the source transmissions, and the monitoring of source performance, take place in the APL-UW Data Center as does the scheduling of the NPAL network receivers, and the processing and archiving of data.

The receivers are scheduled to “turn on” as the signals from the ATOC source arrive at the respective hydrophone arrays. In addition, the NPAL receivers collect and generate ambient noise data in the form of sound power spectral density files integrated over 180 seconds once every 6 minutes. Currently the noise data are only omnidirectional, but we now have permission to collect and process directional ambient sound data. All of this scheduling is rather straightforward, however during LOAPEX the CRON program (software that controls the autonomous network) had to be modified for each of the LOAPEX positions. In addition, a significant effort was spent on monitoring the transmissions from the SPICE04 experiment. In fact, the NPAL network immediately detected the failure of the SPICE04 transducers which led to a valiant effort to attempt repairs by the SIO team.

A previous DURIP allowed for the purchase of new computers and GPS receivers for the NPAL network. The original MS-DOS computers and the GPS receivers are now approximately ten years old and are beginning to fail. We have installed LINUX on the new computers and have kept the original analog to digital converter boards and much of the remaining system hardware. Nevertheless, a significant effort was spent this year rewriting NPAL specific application software to operate in the LINUX environment. The first installation of the new system took place at the Whidbey Island Naval Ocean Processing Facility. The remaining installations will occur next year.

NPAL Seagliders. Another DURIP provided two autonomous underwater vehicles, known as Seagliders. The Seaglider is a small 100-pound vehicle that can be deployed from a small boat by one or two people. Two Seagliders were deployed during the LOAPEX cruise. The vehicles are not powered by a propeller, but rather by buoyancy control; a hydraulic system moves oil in and out of an external bladder to force the glider up or down through the ocean. In addition, the location of the glider’s battery pack can be adjusted to cause the glider’s nose to pitch up or down, or roll its wings to change compass heading. The NPAL Seagliders measured temperature, pressure, salinity, oxygen, and acoustic data while traveling about 2000 miles, and making approximately 600 dives to 1000 m. Since the Seagliders contacted the pilot at APL-UW by Iridium modem each time they surfaced, their position, status, and data were available in near real time. After 191 days at sea the Seagliders were steered to the leeward side of Kauai for pickup on 24 March 2005. Figure 3 illustrates the paths of the two Seagliders along specified acoustic transmission paths during their record breaking deployment.

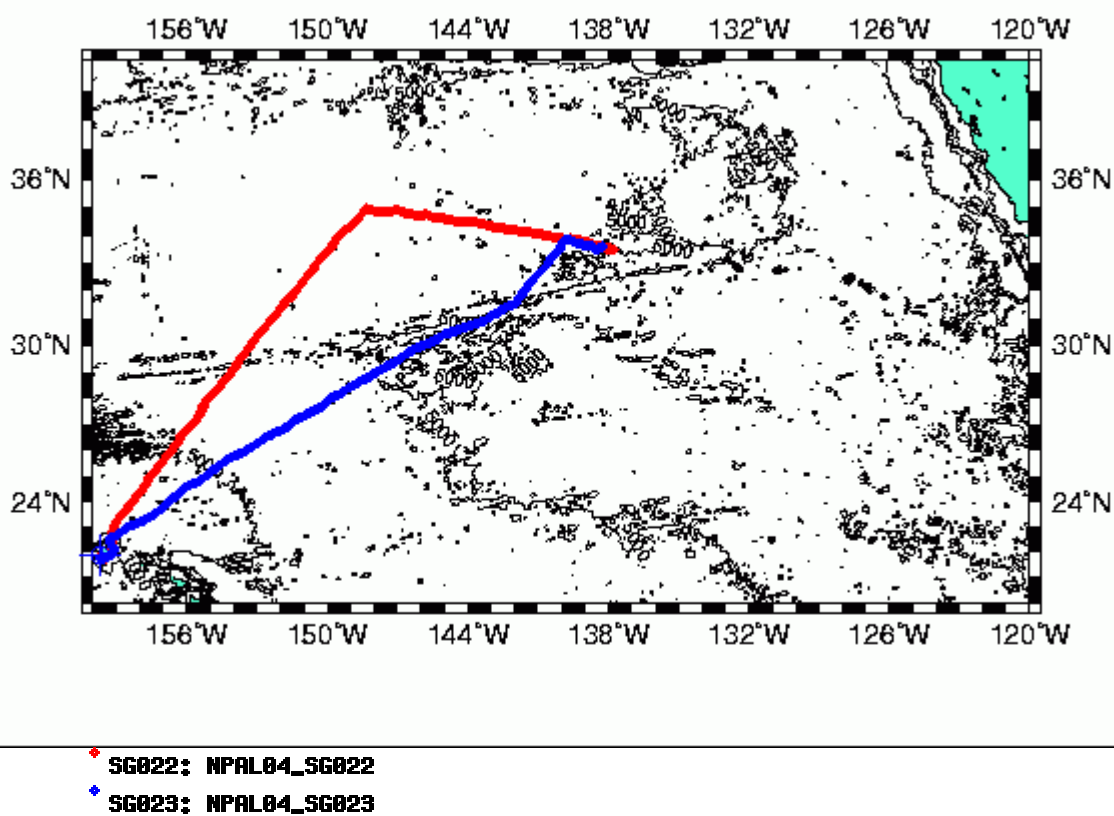


Figure 3. The nearly 2,000 mile paths taken by the two APL-UW NPAL Seagliders.

NPAL Workshop. The eighth NPAL workshop was held near Blaine, Washington on 11-14 May 2005. Approximately 40 researchers were in attendance including seven graduate students. Thirty-eight presentations were given including preliminary results from LOAPEX. Discussions also began on the next major experiment currently scheduled for the 2008-2009 timeframe. The next NPAL workshop will most likely be held in or near San Diego, CA in the Spring of 2006.

RESULTS

Thirteen NPAL-related papers were published in a Special Section (Volume 117) of the *Journal of the Acoustical Society of America*. These papers addressed a wide range of topics including statistical measures of amplitude and phase fluctuations at long ranges, the spatial and temporal coherence of the received signal, signal energy redistribution by mode scattering, horizontal refraction, the implications of ray chaos theory, the effects of bottom interactions, the characteristics of ambient noise on ocean basin scales, and the potential impact of low-frequency transmissions on marine mammals.

Summarized below are examples of results from each of the Work Completed categories discussed above. Space limitations preclude even a representative sampling.

The LOAPEX cruise. In order to check the validity of the LOAPEX experimental timing, source position data, and signal processing, variations in the signal arrival time as measured by the NPAL network receivers were compared to variations in arrival time predicted by the OSU TOPEX/Poseidon

Global Inverse Solution for tidal motion (Egbert et al. (1994)). Tidal water motion predictions are made between each source and receiver location. Since tidal motions produce very small timing variations (order 10 ms) and their phase is predicted well, the comparison offers a good check on the acoustic measurements. As an example, Figure 4 below compares the travel time signal variability predicted by the tidal model with data measured at receiver “R” (Figure 1) during a period of approximately 32 hours, while the ship was located 500 km from the VLAs.

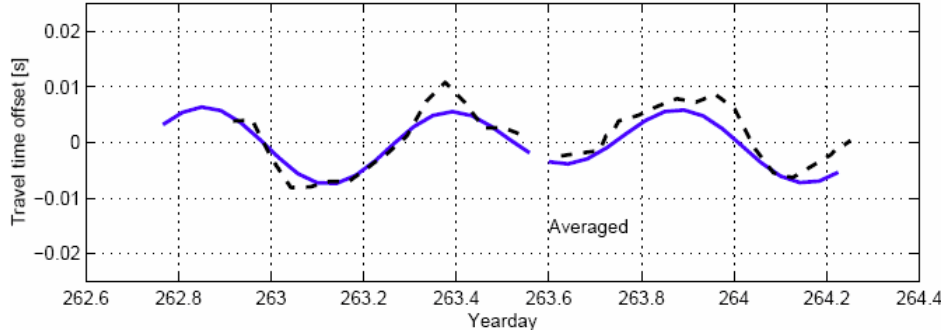


Figure 4. The blue line indicates predicted travel time variations along the path from receiver site “R” to a LOAPEX source location 500 km from the VLAs using a tidal motion model. The dashed line shows the measured travel time variability over a period of 32 hours for the same path. The agreement in amplitude and phase is excellent and suggests high quality acoustic data..

The NPAL network. NPAL network receivers “N” and “O” (Figure 1) were used to estimate horizontal coherence along the paths to the Kauai acoustic source (Andrew et al., 2005). The measured coherence values were then compared (Figure 5) to predictions based upon the CAFI numerical program (Calculates Acoustic Fluctuations due to Internal waves, Flatté and Vera (2003)). The CAFI prediction is seen to be quite close to the measured data. Note also that the spatial coherence is worse (drops off faster) for the Kauai to “O” path than the Kauai to “N” path. As the Kauai to “O” path is *shorter* than the Kauai to “N” path, an argument based solely on range would presume the spatial coherence to be better (i.e., drop off more slowly) on the shorter path. However, the index of refraction variations are more intense along the shorter path, and this causes greater de-coherence along the shorter path. This effect is predicted by theory and observed in the data.

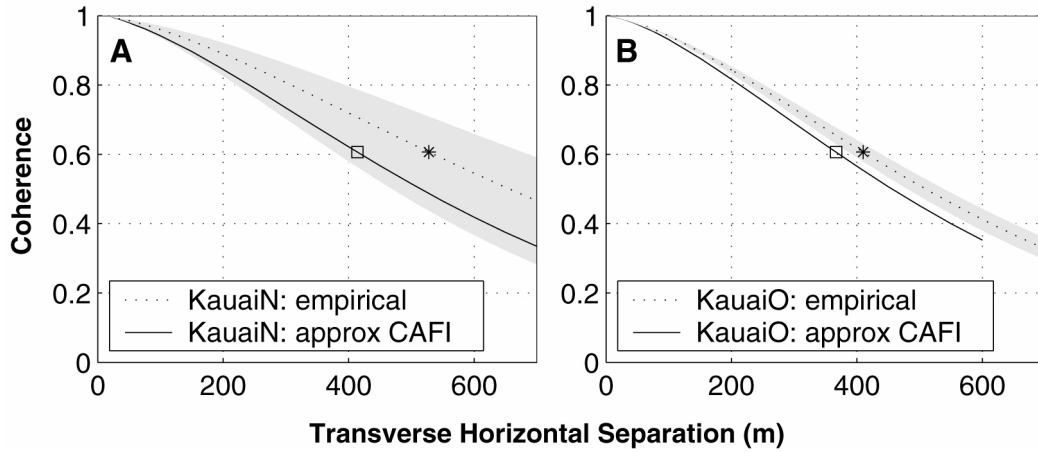


Figure 5. Horizontal coherence estimates for the path between the Kauai acoustic source and the NPAL network receivers “O”(A) and “N”(B) compared to predicted values of coherence based upon the CFI model. The dashed line represents an average estimate based upon multiple years of data and the shaded area reflects a 60% confidence interval. The solid line is the based upon CFI.

NPAL Seagliders. Two NPAL Seagliders were deployed during the LOAEPX cruise. They each traveled about 2,000 miles from the deployment site near the VLA position shown in Figure 2 to their pickup location on the leeward side of Kauai, HI. During these transects each Seaglider dove approximately 600 times to a depth of 1000 m making near continuous measurements of temperature, pressure, salinity, oxygen, and acoustics. Figure 6 presents the ocean temperature data measured on the Seaglider path shown as blue in Figure 3.

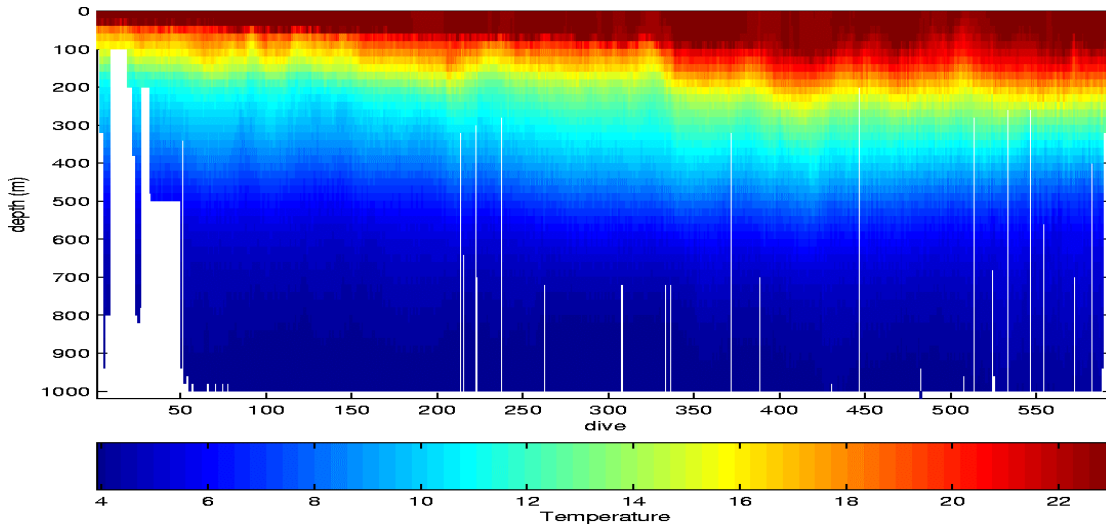


Figure 6. Ocean temperature to a depth of 1000 m as measured by one of the NPAL Seagliders. The horizontal scale is the sequential dive number along the approximate 2,000 mile path.

The NPAL workshop. At the NPAL workshop Dan Rudnick reported preliminary results for his Underway CTD (UCTD). The UCTD was deployed during LOAPEX, without support from Rudnick's group, over approximately 2,000 km of the east to west transect. Figure 7 is based on the UCTD data and shows variability in sound speed as a function of depth, averaged over 13 km section, due to Spice, Tilt (internal waves), and the total variability. Spice is comparable to tilt below the mixed layer. Internal waves produce significantly more variability in sound speed at the shallower depths. The data were taken in September 2004 before the winter mixing.

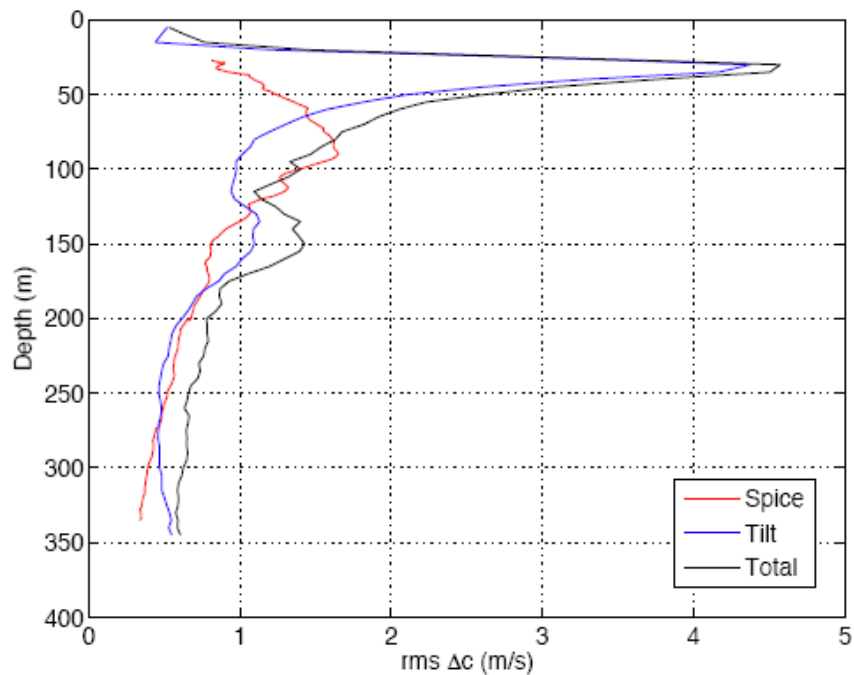


Figure 7. *Sound speed variability versus depth due to Spice (red), Tilt i.e., internal waves (blue), and the total variability due to both (black). Spice is comparable to tilt below the mixed layer. Internal waves produce significantly more variability in sound speed at the shallower depths. The data were taken in September 2004 before the winter mixing.*

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic surveillance or remote sensing of the ocean interior. The data from the NPAL network, and the special NPAL experiments, indicate that existing systems do not begin to exploit the ultimate limits of acoustic coherence at long ranges in the ocean.

Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetric, and other data types with ocean general circulation models have the potential to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of gyre-scale ocean variability on seasonal and longer time scales.

TRANSITIONS

The Seaglider autonomous vehicle, developed by APL-UW and the Department of Oceanography at the University of Washington, has matured to the point where a cost center has been established to allow regular production of the Seaglider for other institutions and various agencies of the government.

RELATED PROJECTS

(i) D. Rudnick (SIO) were supported by ONR Code 322PO to make SeaSoar and Underway CTD (UCTD) measurements, and to provide UCTD hardware for use during LOAPEX.

(ii) A. Baggeroer (MIT) and K. Heaney (OASIS) were supported by ONR Code 321OA to make horizontal line array measurements during BASSEX.

(iii) A large number of additional investigators are involved in ONR-supported research related to the NPAL project and participate in the NPAL Workshops, including J. Beron-Vera (UMiami), M. Brown (UMiami), J. Colosi (NPS), S. Flatté (UCSC), F. Henyey (APL-UW), V. Ostachev (NOAA/ETL), S. Tomsovic (Washington State), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), M. Wolfson (APL-UW), and G. Zaslavsky (NY Univ.).

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